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A Simplified Analytic Investigation of the Riverside Effects of Sediment Diversions

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INTRODUCTION: Coastal land loss is a striking reality in many coastal communities. The issue is especially acute in coastal Louisiana. Problems of land loss in coastal Louisiana have been extensively documented (Gagliano 1981; Britsch and Dunbar 1993; Boesch et al. 1994; Day et al. 2000). There are several factors that have been identified as causes of this land loss. Among others, these include the following:

- The rate of relative sea level rise in coastal Louisiana, which is generally faster than the rate of marsh accretion (due primarily to regional subsidence).
- The reduction of sediment loads in the Mississippi River.
- The decreased sediment supply to the wetlands due to the lack of hydraulic connection between the wetlands and the Mississippi River.
- The introduction of dredged canals that criss-cross the marshes and expose marsh vegetation to increased currents and salinity.
- Other factors, such as vegetation losses due, for example, to nutria, etc.

As part of an effort to build land in coastal Louisiana, planners are considering the construction of sediment diversions. Sediment diversions typically consist of lateral water diversions, either controlled or uncontrolled, that are designed to capture and remove large quantities of sediment from a river. In coastal Louisiana, these diversions are intended to re-introduce sediment into shallow bays and degraded coastal marshes, in order to rebuild land in these systems (CPRA 2012).

In order for a sediment diversion to be implemented successfully, a variety of factors need to be evaluated. A given sediment diversion must be able to divert and distribute sufficient sediment to effectively mitigate the causal land loss factors listed above. However, the diversion design is subject to several additional constraints. These include the following:

- Physical constraints such as the available hydraulic head differential and sediment supply.
- Riverside impacts such as changes to the main channel hydraulics and sedimentation associated with the diversion.
- Environmental and ecological effects such as changes in the salinity and nutrient loads.

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Given the complexities inherent in a full analysis of all of these factors, it is advantageous to have a set of simplified tools that can be used to make informed, screening level assessments of proposed diversion projects.

To this end, this technical note provides an analytic assessment of one of the primary constraints associated with sediment diversion design: the riverside effects of sediment diversions. This document includes the following:

- A discussion of the fundamental principles of the physics of sediment diversions.
- A qualitative analysis of the primary riverside effects of diversions.
- Analytic tools to yield quantitative estimates of these effects.

GENERAL OVERVIEW OF THE RIVERSIDE EFFECTS OF SEDIMENT DIVERSIONS:

Sediment diversions can change riverside hydraulics and sediment transport. Hydraulic effects include changes to steady flow phenomena, such as backwater and drawdown effects, and changes to unsteady flow phenomena, such as flood hydrograph characteristics. Sediment transport effects include changes to sediment supply, sediment gradation, and river morphology. Although both bed material load (sediment grain sizes found in appreciable quantities in the bed) and wash load (finer grain sizes having minimal interaction with the bed) are affected by diversions, the behavior of the bed material load is the dominant factor associated with morphologic response. In large alluvial rivers, the bed material load is typically composed of non-cohesive (sand and gravel) sediments and the wash load is composed of cohesive (silt and clay) sediments. By contrast, in estuaries, cohesive sediments may become a significant component of the bed material load. For example, in the Mississippi River near the Old River Control Complex (located far upstream of the river mouth), the bed material load consists of gravels and sand larger than 125 microns while the wash load is composed of cohesive sediments (smaller than 62.5 microns) and very fine sands (ranging from 62.5 to 125 microns). In contrast, the bed material load in Southwest Pass (located at the river mouth) includes flocculated cohesive sediments, very fine sand, and smaller quantities of coarser grain sizes whose supply is limited by upstream deposition, while the wash load consists of very fine silts and clays.

Non-cohesive sediment transport is generally characterized by two separate modes of transport: bed load and suspended load. Bed load is sediment that moves by rolling, skipping, or sliding along the bed. Bed load typically moves in waves along the riverbed, and is responsible for the dune fields observed along river bottoms. Suspended load is sediment that is carried into the water column by turbulent bursts, and moves over relatively long distances due to repeated re-suspension from turbulence (ASCE 2008). It is important to consider the characteristics of each of these sediment transport modes when analyzing river processes.

Even though non-cohesive sediment occasionally is referred to colloquially as *bed load*, this association is misleading, as it implies that all non-cohesive sediment moves as bed load. In reality, non-cohesive sediment can move as either bed load or suspended load or both, depending on the sediment size and the available energy in the flow. Often, the majority of the non-cohesive sediment load is carried as suspended load. For example, observations in the Mississippi River near the Old River Control Complex show that the bed load can vary from 40 percent of the total non-

cohesive load for low flows, to less than 10 percent of the total non-cohesive load for high flows (Little et al. 2012).

IDEALIZED SEDIMENT DIVERSION RIVERSIDE EFFECTS ANALYSIS: The following analysis is based on the fundamental framework for an idealized sediment diversion established in Letter et al. (2008). The analysis presented here extends this framework to include both bed load and suspended load transport modes, and to include upstream and downstream non-equilibrium effects. Since morphologic response of the river is dominated by non-cohesive sediment transport, only non-cohesive sediment is considered in the following analysis.

Simplifications and Initial Conditions. Consider a river modeled as a wide rectangular channel of constant width (Figure 1). The discharge in the river is steady (or quasi-steady) and initially at uniform conditions (i.e., the depth, h , is constant and the hydraulic slope, S , is equal to the bed slope, S_b). There are three river cross sections defined along the river, labeled as 1, 2, and 3. A sediment diversion is placed in the river just downstream of cross section 2. It has a cross section labeled D. Cross section 1 is sufficiently far upstream of cross section 2 to be upstream of the drawdown effects of the diversion (i.e., it maintains uniform flow conditions throughout the analysis). It is also assumed that the water diversion is a relatively small fraction of the total river discharge (e.g., less than 25 percent).

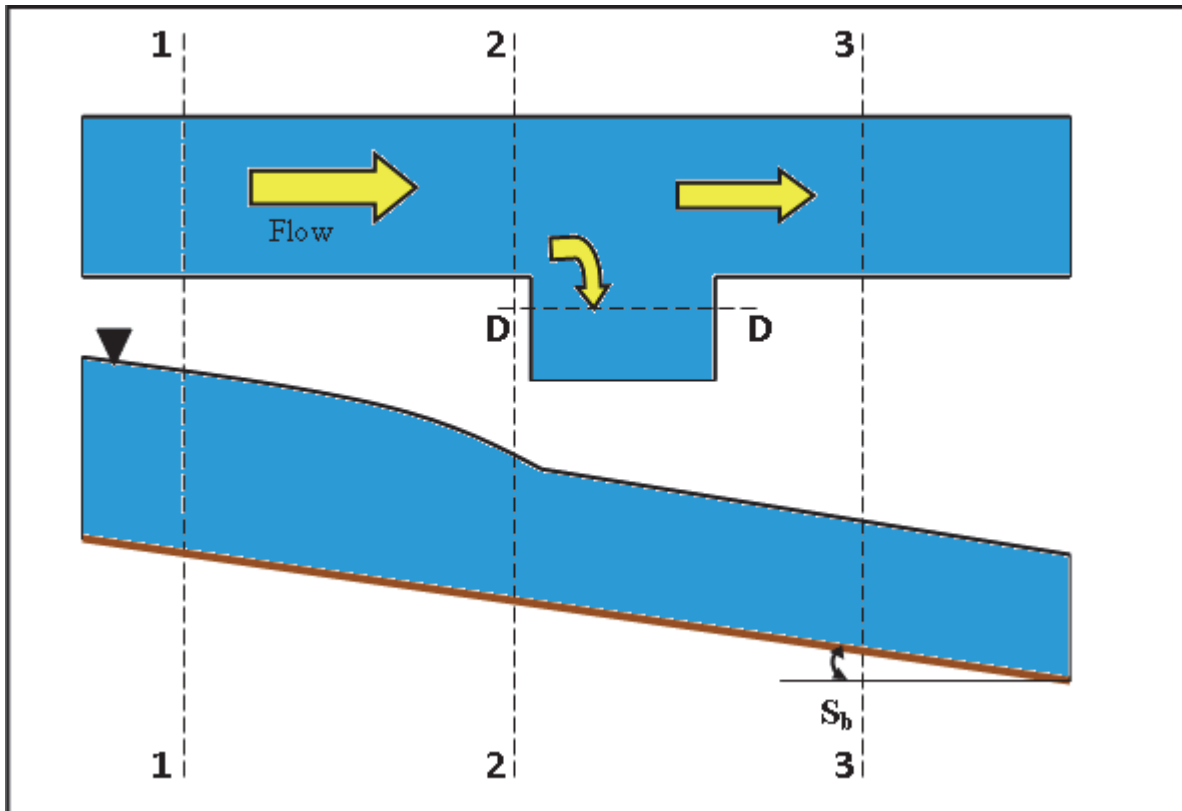


Figure 1. Diversion and river schematics.

Assume that Manning's equation for a wide rectangular channel is valid for all cross-sections, i.e.,

$$Q = \frac{K_n}{n} b h^{5/3} S^{1/2} \quad (1)$$

Non-cohesive sediment flux can be shown to be proportional to the stream power (stream power per unit bed area), by both physical reasoning and by comparison to measured data (Bagnold 1966; Yang 1972, 1973). For this analysis, non-cohesive suspended load and bed load sediment transport are expressed as power law functions of the stream power. These power law functions represent sediment transport potentials; they indicate the transport rate assuming 100 percent of the sand grains in the sediment bed are available for that mode of transport. In order to express these potentials as actual rates of transport, they must be multiplied by the fraction of grains available for each particular mode of transport.

It is assumed that 100 percent of the grains at the bed surface are in motion: i.e., the critical shear stress for all grains at the bed surface is exceeded by the bed shear stress. Let β_s be defined as the fraction of grains in the bed moving as suspended load, and $(1-\beta_s)$ be defined as the fraction of grains moving as bed load. Using these definitions, and power law functions of stream power to quantify the transport, the equations for suspended load and bed load transport are given as follows:

$$Q_{S.S} = \beta_s Q_{S.POT} = \beta_s \alpha_s b \left(\frac{\rho Q S}{b} \right)^{n_s} \quad (2)$$

$$Q_{S.B} = (1 - \beta_s) Q_{B.POT} = (1 - \beta_s) \alpha_b b \left(\frac{\rho Q S}{b} \right)^{n_b} \quad (3)$$

It is worth noting that Yang (1972, 1973) recommends the use of the unit stream power, or power per unit weight of water, rather than the stream power used here. However, for a given river discharge, if the depth changes little over the spatial domain of the analysis, the two methods yield similar results. Therefore, the stream power is used instead of the unit stream power because it simplifies the analysis.

Drawdown Induced Increase in Sediment Load Upstream of the Sediment Diversion Upon Initiation of Diversion Operations. When diversion operations are initiated, the river upstream of the diversion accelerates toward the diversion site. This results in a drawdown of the water surface. This drawdown will be steepest just upstream of the diversion, but can extend for many miles upstream, depending on the slope of the river (the milder the river slope, the further upstream the drawdown will extend).

The flows at cross-sections 1 and 3 are initially uniform (as time progresses, morphologic changes in the river will alter this condition at cross-section 3); hence, initially, the hydraulic slope is equal to the bed slope at both locations. Maintaining the conservation of water mass and applying Manning's equation at sections 1 and 3, the following equation results:

$$\frac{K_n}{n} b h_1^{5/3} S_b^{1/2} = \frac{1}{(1 - \delta_D)} \frac{K_n}{n} b h_3^{5/3} S_b^{1/2} \quad (4)$$

This reduces to the following expression for the downstream to upstream depth ratio:

$$\frac{h_3}{h_1} = (1 - \delta_D)^{3/5} \quad (5)$$

Near the diversion (cross section 2), the hydraulic slope is not equal to the bed slope and the hydraulic slope must be determined. Neglecting local momentum losses at the diversion site (this assumption introduces little error as long as the diversion discharge fraction is not large), the depths in the river at cross sections 2 and 3 can be set equal to each other. Writing the equivalent of Equation (4) for flow between cross sections 1 and 2, and substituting in Equation (5) to express the entire equation in terms of h_1 yields

$$\frac{K_n}{n} b h_1^{5/3} S_b^{1/2} = \frac{K_n}{n} b h_1^{5/3} (1 - \delta_D) S_2^{1/2} \quad (6)$$

Where S_2 is the hydraulic slope at cross section 2, which is not equal to the bed slope.

This reduces to the following expression for the hydraulic slope ratio:

$$\frac{S_2}{S_b} = (1 - \delta_D)^{-2} \quad (7)$$

Note that, although the maximum drawdown occurs at the diversion site, the effects of the drawdown can be detected for a considerable distance upstream of the diversion site. This distance is called the drawdown influence length (L_{DI}).

The drawdown influence length can be estimated by performing a numerical integration of the drawdown curve and defining the influence length in terms of the distance upstream, required for the drawdown to reduce to a given percentage of the maximum drawdown. For this analysis, two percentages were chosen: 50% ($L_{DI50\%}$) and 1% ($L_{DI1\%}$).

From Equation (5), the maximum drawdown (i.e., the drawdown at the diversion site) can be expressed in terms of the flow diversion fraction, δ_D . Therefore, the drawdown influence length can also be expressed in terms of δ_D . The numerical integration of the drawdown curve can be performed over a wide range of flow diversion fractions (0 to 0.5), and the results can be approximated to a high degree of accuracy with linear regression. This yields simple, approximate equations for the drawdown influence length:

$$L_{DI50\%} = \frac{h_1}{S_b} (0.27(1 - \delta_D)^{3/5} - .066) \quad (8)$$

$$L_{DI1\%} = \frac{h_1}{S_b} \left(0.57(1 - \delta_D)^{3/5} + .082 \right) \quad (9)$$

For example, for a river with a bed slope of 0.00005 and an average depth of 40 ft (approximate conditions for the Lower Mississippi River) and a flow diversion fraction of 0.1, $L_{DI50\%}=150,000$ ft (28.4 miles) and $L_{DI1\%}=494,000$ ft (93.5 miles). In qualitative terms, this means that the diversion drawdown has a relatively significant impact on the river within 28.4 miles upstream of the diversion site, and the diversion drawdown has a detectable (though small) impact on the river within 93.5 miles upstream of the diversion site.

Equation (7) can be used together with Equations (2) and (3) to solve for the adjustments of the upstream sediment fluxes due to the drawdown. This is done by defining a river cross-section saturation ratio at cross section 2 (ϕ_2) such that the quantity ($\phi_2\beta_{S,2}$) represents the ratio of drawdown induced suspended load to the equilibrium suspended load potential (i.e., $\phi_2\beta_{S,2}=Q_{S,2}/Q_{S,POT}$) and the quantity $\phi_2(1-\beta_{S,2})$ represents the ratio of drawdown induced bed load to the equilibrium bed load potential (i.e., $\phi_2(1-\beta_{S,2})=Q_{B,2}/Q_{B,POT}$):

$$\phi_2\beta_{S,2}\alpha_S b \left(\frac{\rho Q S_b}{b} \right)^{n_s} = (1 - \delta_D)^{-2n_s} \beta_{S,1}\alpha_S b \left(\frac{\rho Q S_b}{b} \right)^{n_s} \quad (10)$$

$$\phi_2(1 - \beta_{S,2})\alpha_B b \left(\frac{\rho Q S_b}{b} \right)^{n_B} = (1 - \delta_D)^{-2n_B} (1 - \beta_{S,1})\alpha_B b \left(\frac{\rho Q S_b}{b} \right)^{n_B} \quad (11)$$

These equations can be simplified by canceling common terms:

$$\phi_2\beta_{S,2} = (1 - \delta_D)^{-2n_s} \beta_{S,1} \quad (12)$$

$$\phi_2(1 - \beta_{S,2}) = (1 - \delta_D)^{-2n_B} (1 - \beta_{S,1}) \quad (13)$$

Equations (12) and (13) can be solved for ϕ_2 and $\beta_{S,2}$:

$$\phi_2 = (1 - \beta_{S,1})(1 - \delta_D)^{-2n_B} + \beta_{S,1}(1 - \delta_D)^{-2n_s} \quad (14)$$

$$\beta_{S,2} = \frac{\beta_{S,1}}{\phi_2(1 - \delta_D)^{2n_s}} \quad (15)$$

The values of ϕ_2 and $\beta_{S,2}$ are given by Equations (14) and (15) and are only valid at the initiation of diversion operations. As time progresses, the river adjusts to the presence of the diversion, and the sediment load at cross-section 2 diverges from these solutions and converges on the upstream equilibrium values (i.e., $\phi_2 \rightarrow 1$ and $\beta_{S,2} \rightarrow \beta_{S,1}$).

Sediment Mass Balance at the Sediment Diversion Site. The sediment mass balance for suspended load and bed load at the diversion site can be written in terms of the power law

functions of stream power for river cross-sections 2 and 3 (upstream and downstream of the diversion), and the diversion cross-section D:

$$\phi_2 \beta_{s,2} \alpha_s b \left(\frac{\rho Q S_b}{b} \right)^{n_s} - \varepsilon_D \delta_D \phi_2 \beta_{s,D} \alpha_s b \left(\frac{\rho Q S_b}{b} \right)^{n_s} = \phi_3 (1 - \delta_D)^{n_s} \beta_{s,3} \alpha_s b \left(\frac{\rho Q S_b}{b} \right)^{n_s} \quad (16)$$

$$\begin{aligned} \phi_2 (1 - \beta_{s,2}) \alpha_B b \left(\frac{\rho Q S_b}{b} \right)^{n_B} - \varepsilon_D \delta_D \phi_2 (1 - \beta_{s,D}) \alpha_B b \left(\frac{\rho Q S_b}{b} \right)^{n_B} = \\ \phi_3 (1 - \delta_D)^{n_B} (1 - \beta_{s,3}) \alpha_B b \left(\frac{\rho Q S_b}{b} \right)^{n_B} \end{aligned} \quad (17)$$

These equations can be simplified by canceling common terms:

$$\phi_2 (\beta_{s,2} - \varepsilon_D \delta_D \beta_{s,D}) = \phi_3 (1 - \delta_D)^{n_s} \beta_{s,3} \quad (18)$$

$$\phi_2 ((1 - \beta_{s,2}) - \varepsilon_D \delta_D (1 - \beta_{s,D})) = \phi_3 (1 - \delta_D)^{n_B} (1 - \beta_{s,3}) \quad (19)$$

In these equations, saturation ratios are specified for the river cross-sections and a sediment diversion efficiency is defined for the diversion. The saturation ratio for river cross-section 3 (ϕ_3) is defined in a manner consistent with the way saturation ratio (ϕ_2) is defined in the drawdown analysis: i.e., ($\phi_3 \beta_{s,3}$) represents the ratio of the residual suspended load in the river (downstream of the diversion) to the equilibrium suspended load potential. The sediment diversion efficiency (ε_D) is defined such that the quantity ($\beta_{s,D} \varepsilon_D$) represents the ratio of the suspended sediment concentration being diverted ($\beta_{s,D} Q_{SD,S}/Q_D$) to the suspended sediment concentration potential in the river just upstream of the diversion site ($\phi_2 Q_{S,POT}/Q$), and the quantity ($(1 - \beta_{s,D}) \varepsilon_D$) represents the ratio of the bed load concentration being diverted ($((1 - \beta_{s,D}) Q_{SD,B}/Q_D)$) to the bed load concentration potential in the river just upstream of the diversion site ($\phi_2 Q_{B,POT}/Q$).

Solutions for Mass Balance at the Diversion Site for both Downstream Equilibrium and Downstream Non-equilibrium Conditions. To find the required diversion conditions to achieve downstream sediment equilibrium in the river, the downstream saturation ratio (ϕ_3) is set equal to 1 and Equations (18) and (19) are solved for $\varepsilon_{D,EQ}$ and $\beta_{s,3,EQ}$:

$$\varepsilon_{D,EQ} = \frac{\phi_2 \left[(1 - \beta_{s,2}) + \beta_{s,2} (1 - \delta_D)^{(n_B - n_s)} \right] - (1 - \delta_D)^{n_B}}{\delta_D \phi_2 \left[(1 - \beta_{s,D}) + \beta_{s,D} (1 - \delta_D)^{(n_B - n_s)} \right]} \quad (20)$$

$$\beta_{s,3,EQ} = \frac{\phi_2 (\beta_{s,2} - \delta_D \varepsilon_D \beta_{s,D})}{(1 - \delta_D)^{n_s}} \quad (21)$$

To find the downstream conditions in the river (generally nonequilibrium) that result from a given set of diversion conditions, the diversion efficiency (ε_D) is specified, and Equations (18) and (19) are solved for ϕ_3 and $\beta_{s,3}$:

$$\phi_3 = \phi_2 \left([(1 - \beta_{s,2}) - \delta_D \varepsilon_D (1 - \beta_{s,D})] (1 - \delta_D)^{-n_B} + [\beta_{s,2} - \delta_D \varepsilon_D \beta_{s,D}] (1 - \delta_D)^{-n_S} \right) \quad (22)$$

$$\beta_{s,3} = \frac{\phi_2 (\beta_{s,2} - \delta_D \varepsilon_D \beta_{s,D})}{\phi_3 (1 - \delta_D)^{n_S}} \quad (23)$$

Approximate Values for Input Parameters. In order to make practical use of the equations provided, it is necessary to assign reasonable values for the input parameters. These input parameters include n_B , n_S , $\beta_{s,1}$, $\beta_{s,D}$, ε_D , and δ_D .

The exponents for the power law stream power transport equations, n_B and n_S , can be assigned values based on theoretical considerations and observed values of these terms in natural flows.

Several of the empirical and semi-theoretical relationships for bed load transport exhibit a near linear relationship between the rate of transport and stream power (Meyer-Peter and Müller 1948; Bagnold 1966; Wong and Parker 2006). However, others exhibit a non-linear relationship (Bagnold 1977; van Rijn 1984a). The distinction between these relationships appears to be due, at least in part, to whether or not the equations are formulated to include the additional stream power required for the initiation of motion of the coarser bed grains. Hence, it is reasonable to expect a nonlinear relationship between bed load transport and stream power at low transport rates (when the applied bed shear stress is near incipient motion) and a more nearly linear relationship at high transport rates (when most of the grains are in constant motion).

In Little et al. (2012), a bed load rating curve is given for the Mississippi River at the Old River Control Complex. The rating curve is based on a series of bed load measurements obtained using the ISSDOTv2 method of bed load quantification from sequential bathymetric surveys (Abraham et al. 2011). The Old River Control Complex is located approximately 300 miles upstream from the river mouth, and the stream power is sufficient to keep most of the bed grains in motion for the observed discharge rates. This rating curve exhibits a near-linear relationship with the river discharge. By contrast, bed load data collected in the lowermost Mississippi River exhibit a near-exponential relationship with river discharge (Allison 2010). These data are collected near Empire, Louisiana, located 25 miles upstream of the river mouth. For lower discharge rates, the stream power at this site is insufficient to keep most of the bed grains in motion.

(Note also that supply limited conditions prevail at the Empire reach. This supply limitation inhibits the establishment of a unique relationship between stream power and bed load transport. The influence of supply limited conditions is discussed in the Other Important Considerations section of this report).

These data suggest that, for the purposes of establishing parameters for this analysis, the bed load transport conditions in the Lower Mississippi River can be approximated in terms of the theoretical categories given above. That is, for relatively high discharge conditions where most of the bed grains are in motion, a near-linear relationship exists between bed load and stream power, but for lower discharge conditions, the additional stream power required to initiate motion contributes to a nonlinear relationship between bed load transport and stream power. Since most sediment flux and morphologic change occurs during high discharge conditions, the linear relationship associated with high discharge conditions will be invoked in this analysis.

For suspended load transport, observations and transport equations generally demonstrate a more nonlinear relationship than for bed load. Transport equations are generally expressed in terms of the near bed suspended sediment concentration. The suspended sediment flux can then be expressed as the cross-sectionally averaged concentration (as a function of the near-bed concentration) times the water discharge. This means that the existence of a near-linear relationship between suspended sediment flux and stream power would require that the concentration be a constant value, independent of the water discharge. However, the transport equations in the published literature express the near bed concentration as a non-linear function of the bed shear stress (van Rijn 1984b; Garcia and Parker 1991; Zyserman and Fredsøe 1994). Hence, the suspended non-cohesive sediment flux must in general be given as a nonlinear function of the stream power.

A curve fit of the depth-averaged suspended sand concentration versus discharge for observations at the Mississippi River at Vicksburg yields a near linear relationship (Copeland 2009). This implies a near-quadratic relationship between suspended non-cohesive sediment load and stream power in the Lower Mississippi River.

Based on these general observations, for the purposes of this analysis, n_B and n_S have assigned values of 1 and 2, respectively.

The inflowing suspended load fraction varies widely in natural flows. However, based on observations from flume experiments, the suspended non-cohesive load represents 80 - 90 percent of the total non-cohesive load for flows where the shear velocity is greater than three times the settling velocity of the sediment (van Rijn 1984b). This criterion is typically satisfied for a large low-gradient river like the Mississippi River, when it is flowing at or near the channel forming discharge. Hence, a 90 percent suspended load fraction is a reasonable assumption for this exercise.

In order to achieve a 90 percent suspended load fraction, it is necessary to specify the fraction of grains in the bed that move as suspended load ($\beta_{S,1}$) such that the product of this fraction and the suspended load potential equals 90 percent of the total load. Since the suspended load potential is typically larger than the bed load potential (for the channel forming discharge in low gradient rivers), the fraction needed must be somewhat less than 0.9. Therefore, for this analysis, the fraction of bed grains moving as suspended load is set equal to 0.8.

Intuitively, the suspended fraction diverted ($\beta_{S,D}$) should be inversely proportional to the sediment diversion efficiency, ε_D . This is because ε_D is generally a function of how effectively the diversion captures the near-bed portion of the water column in the river, since this is the most sediment rich zone of the water column. Assuming a linear inverse proportionality, with $\beta_{S,D} = \beta_{S,2}$ at $\varepsilon_D = 1$, the following expression is derived for $\beta_{S,D}$:

$$\beta_{S,D} = 1 - \varepsilon_D (1 - \beta_{S,2}) \quad (24)$$

Note that introducing Equation (24) into Equation (20) results in a nonlinear solution for $\varepsilon_{D,EQ}$ that can be solved iteratively:

$$\varepsilon_{D.EQ} = \left(\frac{\phi_2 \left[(1 - \beta_{S.2}) + \beta_{S.2} (1 - \delta_D)^{(n_B - n_S)} \right] - (1 - \delta_D)^{n_B}}{\delta_D \phi_2 \left[(1 - \beta_{S.2}) + \left(\frac{1}{\varepsilon_{D.EQ}} - (1 - \beta_{S.2}) \right) (1 - \delta_D)^{(n_B - n_S)} \right]} \right)^{1/2} \quad (25)$$

For the equilibrium case, one would solve for $\varepsilon_{D.EQ}$. However, it also is useful to investigate the riverside effects of a diversion that does not yield equilibrium conditions downstream. For the purposes of this analysis, a value of ε_D was selected that represents an equal diversion of water and sediment, i.e., $\varepsilon_D = 1$. Since δ_D can vary widely, this will be used as the independent variable. Hence, for the purposes of this analysis the values of the input parameters are given as follows:

$$\begin{aligned} n_B &= 1 \\ n_S &= 2 \\ \beta_{S.1} &= 0.8 \\ \beta_{S.D} &= f(\beta_{S.2}, \varepsilon_D) \\ \varepsilon_D &= 1 \text{ (for the non-equilibrium case)} \end{aligned}$$

Practical Preliminary Assessment Curves for Low Gradient Rivers. Using Equations (14), (15), (21), (22), (23), and (25) together with the input parameters defined above, it is possible to develop simplified relations between diversion and riverside transport responses.

Figure 2 depicts the initial increase in the riverine sediment load at the diversion site due to the drawdown induced by the diversion (Equations (14) and (15)). Note that the increase is significant, with even a 10 percent flow diversion resulting in a 47 percent increase in the saturation ratio. The suspended load fraction increases for all diversion rates, indicating that the drawdown will result in a higher percentage of the bed material moving in suspended load. This is because the suspended load response to changes in the stream power is more nonlinear than the bed load response. Therefore, the increase in stream power due to the drawdown results in a disproportionate increase in the fraction of bed grains moving in suspended load.

As was stated previously, this increase in sediment load represents the initial response of the river to the opening of the diversion. As time progresses, the upstream river morphology adjusts to the presence of the diversion, and the sediment load converges on the upstream equilibrium value (i.e., $\phi_2 \rightarrow 1$ and $\beta_{S.2} \rightarrow \beta_{S.1}$). To represent the downstream effects of these two different conditions, the remaining results are cast in terms of *short term* and *long term* conditions, with the short term conditions for ϕ_2 and $\beta_{S.2}$ given by Figure 2, and the long term conditions given by the upstream equilibrium conditions (i.e., $\phi_2 \rightarrow 1$ and $\beta_{S.2} \rightarrow \beta_{S.1}$).

Figure 3 shows the sediment diversion efficiency required to maintain downstream equilibrium (Equation (25)). It depicts the values for both the short term conditions, where the upstream reach is saturated with sediment due to the drawdown of the river upstream of the diversion, and the long term conditions, where the upstream reach has adjusted to the drawdown and re-established equilibrium.

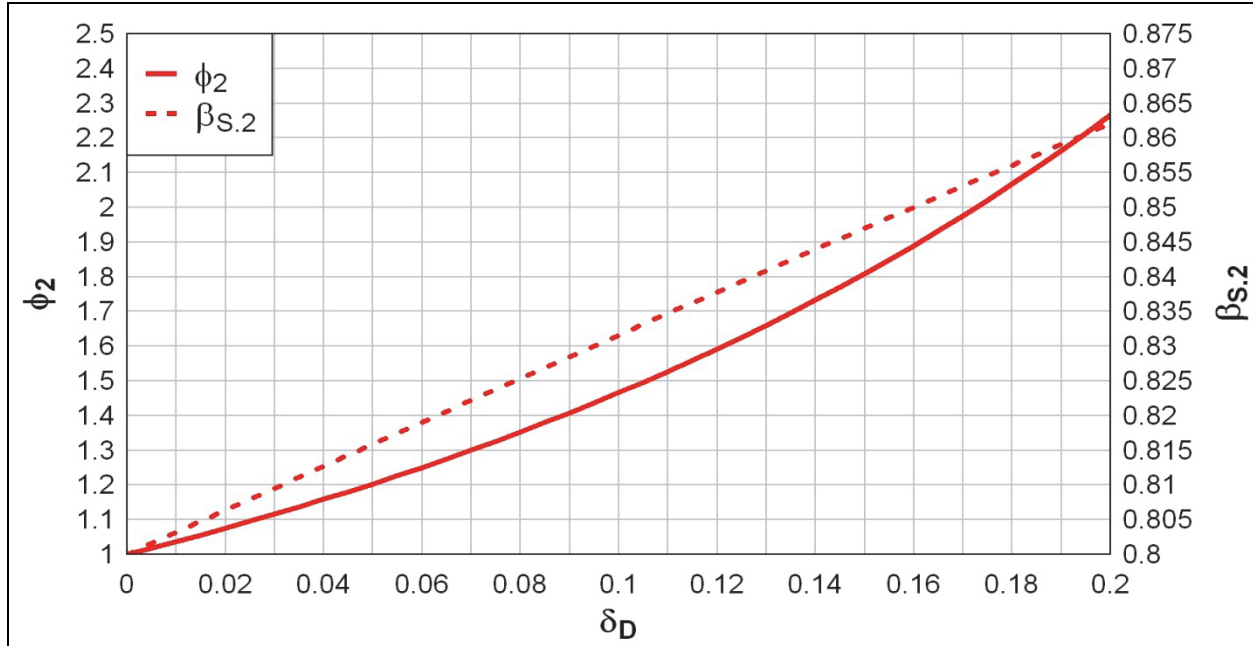


Figure 2. Upstream sediment load saturation due to drawdown effects

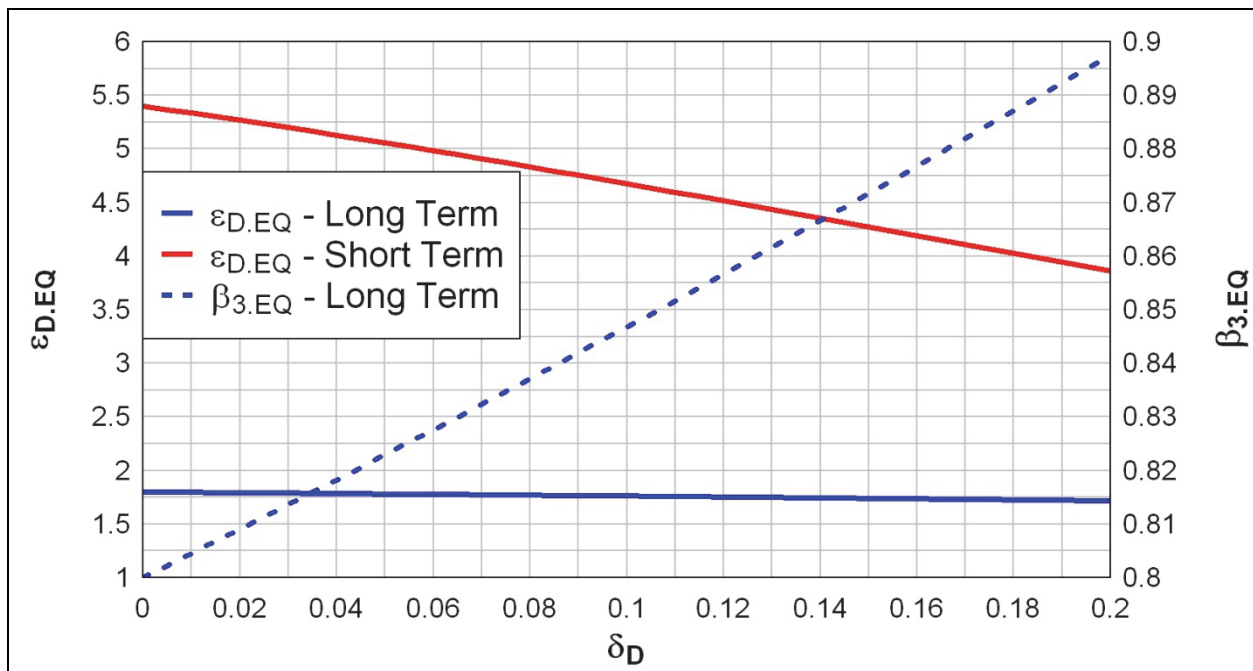


Figure 3. Sediment diversion efficiency required to maintain downstream equilibrium for short term (just after diversion operations commence) and long term river conditions (i.e., $\phi_2 > 1$ and $\phi_2 = 1$)

The short term value varies from around 5 at low diversion ratios, to around 3.5 at a diversion ratio near 0.2. This result is somewhat inflated by the need to compensate for a large bed load fraction that is being diverted (according to Equation (24)), but even if this requirement is relaxed, a very large equilibrium sediment diversion ratio is still required to maintain equilibrium in the short term. Therefore, for all practical purposes the analysis indicates that it is not feasible

to design a diversion that will be in downstream equilibrium in the short term, due to the drawdown induced increase in sediment load.

The long term value is between 1.7 and 1.8 for all of the diversion discharge fractions given (0 to 0.2). It is possible to design a diversion that captures this much sediment, but to do so generally requires that the diversion be designed to exploit typical heterogeneous transport processes in the river, such as sorting around river bends, sediment storage in lateral bars, and sediment stratification in the water column.

Figure 3 also contains the fraction of bed grains moving as suspended load for the upstream equilibrium case (long term). Note that this fraction increases for all diversion rates. This is due to the way that $\beta_{S,D}$ has been determined with Equation (24). Equation (24) tends to bias the diversion fraction towards bed load for sediment diversion efficiency values greater than 1. However, since the suspended load response to changes in the stream power is more nonlinear than the bed load response, the only way to keep the bed gradation downstream the same as the upstream gradation would be to divert a disproportionately greater suspended load fraction. In practice, however, it is not possible to design a diversion that is both sediment rich and disproportionately diverts grains moving in suspended load, since the highest concentration of suspended load is found near the bed (where the bed load is).

Hence, for the equilibrium diversion case, the river downstream of the diversion will tend to have a larger bed grain fraction moving in suspended load than the river upstream of the diversion. Since coarser grains tend to move as bed load, and finer grains tend to move as suspended load, this means that the bed gradation will tend to be finer downstream of the diversion than upstream of the diversion.

The long term equilibrium value of $\varepsilon_{D,EQ}$ (1.7 to 1.8) can often be achieved with a diversion designed to access sediment-rich environments in the river (e.g., at the inside of a river bend). However, the ability to transport this sediment-rich water through the diversion site and out of the receiving area is constrained by the available potential energy (head difference) at the diversion site and long-term local morphological adjustments. Also, factors other than river physics can limit the selection of a potential diversion site to such an extent that it is not possible to design a sediment-rich diversion. For these reasons, it is useful to investigate the effects of a diversion with a sediment diversion efficiency value less than the equilibrium value. For this exercise, a value of 1 was selected.

Figure 4 depicts the downstream effects on the sediment load of a diversion with a sediment diversion efficiency of 1, using Equations (24) and (25) and $\varepsilon_D = 1$. Note that the short term effects are significant in comparison with the long term effects. With a 10 percent flow diversion, the short term effect is a 60 percent increase in the saturation ratio, whereas the long term effect is a 9 percent increase in the saturation ratio.

As with the equilibrium diversion case, the fraction of bed grains moving as suspended load increases for all diversion rates. However, the amount of this increase is less than for the equilibrium case. This is due to the way that $\beta_{S,D}$ has been determined with Equation (24). Since the value of $\beta_{S,D}$ associated with $\varepsilon_D = 1$ is greater than the value associated with the equilibrium

condition (for which $\varepsilon_D > 1$), the impact on the bed gradation downstream of the diversion is less significant than for the equilibrium case.

This indicates that, in general, a sediment diversion will tend to induce downstream conditions for which a greater fraction of grains move as suspended load (a finer sediment bed). This downstream fining effect is more pronounced for sediment rich diversions than for sediment poor diversions since sediment rich diversions tend to divert a higher proportion of bed load than sediment poor diversions do.

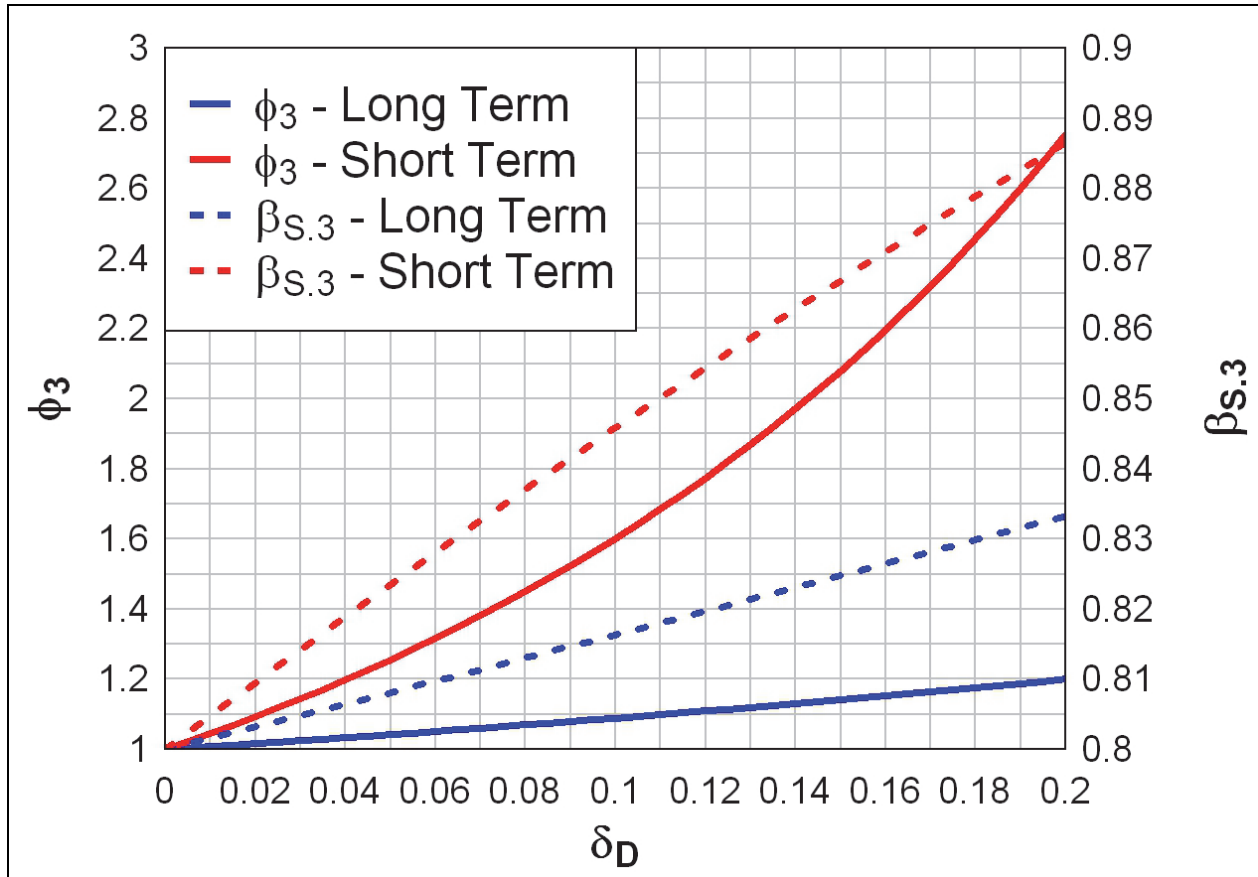


Figure 4. Short term and long term effects on downstream sediment load saturation induced by a diversion with a sediment diversion efficiency of 1.

Short-Term Morphologic Response to the Presence of a Sediment Diversion. In general, *short term* changes are changes associated with the initial response of the river to the introduction of a diversion. For large rivers, these changes begin at the initiation of diversion operations and last from several years to a decade. *Long term* changes are changes that are associated with the long term adjustment of the river to the presence of the diversion. For a large river, the duration of these changes is typically on the scale of decades (ASCE 2008).

For the purposes of this analysis, short term effects are distinguished from long term effects in two ways, and they are as follows:

- Short term effects include the redistribution of sediment by erosion upstream of the diversion to deposition downstream of the diversion (i.e., $\phi_2 > 1$). Long term effects do not include this redistribution, since it is assumed that the river morphology has adjusted to the drawdown and the river is in equilibrium upstream of the diversion.
- Short term effects are assumed to be unaffected by changes in the river morphology. By contrast, long term effects are closely tied to changes in the river morphology.

It is important to understand the short term effects of a diversion. These effects will dominate the initial response of the river to the opening of a diversion. If the diversion is infrequently operated, these effects will be the dominant effects for the entire life cycle of the diversion. Floodways, such as the Bonnet Carre Diversion on the Mississippi River, are an example of infrequently operated diversions.

Often, the most important effect to quantify is the initial rate of deposition downstream of the diversion upon initiation of diversion operations. This can be estimated by using some basic principles of sediment deposition.

For suspended load, the downstream change in mass flux can be related to the rate of deposition with the following equation, adapted from Garcia and Parker (1991):

$$u \frac{\partial (C_s - C_{s.EQ})}{\partial x} = -\frac{w_s r}{h_3} (C_s - C_{s.EQ}) \quad (26)$$

Where x is the longitudinal distance downstream (along the river thalweg), $C_s - C_{s.EQ}$ is the suspended concentration excess (or saturation) in the river, and r is the ratio of the near-bed concentration to the depth-averaged concentration.

The concentration ratio r can be approximated by vertically integrating a simplified form of the sediment concentration profile given by Rouse (1937). The equation is given as follows (Brown 2010):

$$r = \frac{\frac{15w_s}{\zeta_s u_{f.3}}}{1 - e^{\frac{-15w_s}{\zeta_s u_{f.3}}}} \quad (27)$$

The suspended sediment turbulence correction factor is given by Van Rijn (1984b):

$$\zeta_s = 1 + 2 \left(\frac{w_s}{u_{f.3}} \right)^2 \quad (28)$$

Note that Equation (27) is the equilibrium value of r ; hence, Equation (26) is derived with the implicit assumption that r does not change for non-equilibrium conditions. In reality, r does change, such that it is larger for erosional conditions and smaller for depositional conditions. But, for simplicity, the equilibrium value of r is used here.

The friction velocity at cross-section 3 ($u_{f,3}$) can be found using known quantities:

$$u_{f,3} = \frac{n}{K_n} \frac{\sqrt{g}}{h_3^{7/6} b} Q(1 - \delta_D) \quad (29)$$

Equation (26) can be rewritten in terms of quantities derived from the downstream equilibrium analysis given in Figure 3 (for which $\phi_3 = 1$ by definition) and the short term values for the downstream nonequilibrium analysis given in Figure 4:

$$\frac{Q(1 - \delta_D)}{b} \frac{\partial(\beta_3 \phi_3 - \beta_{3,LT} \phi_{3,LT})}{\partial x} = -w_s r (\beta_3 \phi_3 - \beta_{3,EQ}) \quad (30)$$

Equation (30) can be integrated with respect to x to give an equation for the concentration excess at any distance x downstream of the diversion, relative to the concentration excess just downstream of the diversion ($x = 0$). This ratio is defined here as the suspended concentration excess fraction (f_s):

$$f_s = \frac{(\beta_3 \phi_3 - \beta_{3,EQ})}{(\beta_{3,ST} \phi_{3,ST} - \beta_{3,EQ})} = e^{\frac{-w_s r b}{Q(1 - \delta_D)} x} \quad (31)$$

An analogous relationship can be approximated for bed load. The development is the same as for suspended load, except it is assumed that the sediment profile is at the threshold condition for suspended transport: i.e., $w_s / u_{f,3} = 1$ and for this condition, $r \approx 15$. The equation is given as follows:

$$f_B = e^{\frac{-15 w_s b}{Q(1 - \delta_D)} x} \quad (32)$$

The rate of deposition downstream of the diversion varies as the rate of change of the concentration excess: i.e., it varies exponentially with distance from the diversion site. Therefore, the rate of deposition is dependent on the distance downstream being considered.

For two given distances downstream of the diversion (x_1 and x_2), the average rate of deposition (upon initiation of diversion operations) over the river bed surface area between these two distances can be estimated as follows:

$$\frac{\partial \eta}{\partial t} = \frac{Q(1 - \delta_D)}{b(x_2 - x_1)s(1 - p)} \left[C_{P.S.3} (\beta_{3,ST} \phi_{3,ST} - \beta_{3,EQ}) [(1 - f_{s,x_2}) - (1 - f_{s,x_1})] \right. \\ \left. + C_{P.B.3} ((1 - \beta_{3,ST}) \phi_{3,ST} - (1 - \beta_{3,EQ})) [(1 - f_{B,x_2}) - (1 - f_{B,x_1})] \right] \quad (33)$$

The procedure is given as follows:

- Find $\beta_{3,EQ}$ using Equations (20) (or (25)) and (21).
- Find $\phi_{3,ST}$ and $\beta_{3,ST}$ using Equations (22) and (23) or Figure 4.
- Select two distances downstream of the diversion, x_1 and x_2 .

- Use Equations (31) and (32) to calculate f_S and f_B for x_1 and x_2 .
- Use Equation (33) to calculate the average rate of deposition over this distance.

Note that the values of $C_{PS,EQ,3}$ and $C_{PB,EQ,3}$ represent the values of the equilibrium concentration potential for the downstream flowrate (i.e., $Q(1-\delta_D)$). They can be found from existing rating curves applicable to the site, i.e.,:

$$C_{P.S.3} = \frac{\alpha_S}{\rho} \left(\frac{Q(1-\delta_D)}{b} \right)^{n-1} S_b^n \quad (34)$$

$$C_{P.B.3} = \frac{\alpha_B}{\rho} \left(\frac{Q(1-\delta_D)}{b} \right)^{m-1} S_b^m \quad (35)$$

A sample calculation follows:

Assume the same general input parameters given in the Approximate Values for Input Parameters section of this report, as well as the following additional parameters:

$$\delta_D = 0.2$$

$$C_{P.S.3} = 0.00012 \text{ (in mass of sediment per mass of solute units; this is equal to 120 ppm)}$$

$$C_{P.B.3} = 0.00004 \text{ (in mass of sediment per mass of solute units; this is equal to 40 ppm)}$$

$$w_s = 0.05 \text{ ft/sec}$$

$$n = 0.02$$

$$Q = 1,000,000 \text{ cfs}$$

$$b = 2000 \text{ ft}$$

$$h_3 = 50 \text{ ft}$$

$$p = 0.3$$

$$s = 2.65$$

Using these parameters, the following results can be obtained from Figures 3 and 4:

$$\beta_{3,EQ} = 0.897$$

$$\phi_{3,ST} = 2.75$$

$$\beta_{3,ST} = 0.887$$

And the following results can be obtained from Equations (27) – (33):

From Equation (29), $u_{f,3} = 0.32 \text{ ft/sec}$, and from Equation (27) $r = 2.51$. The remaining results are given in Table 1 for a range of values of x_1 and x_2 .

Table 1. Example calculation of deposition downstream of a diversion immediately after the initiation of diversion operations

x_1 (ft)	x_2 (ft)	$f_{S.x_1}$	$f_{S.x_2}$	$f_{B.x_1}$	$f_{B.x_2}$	$\frac{\partial \eta}{\partial t}$ (ft/sec)	$\frac{\partial \eta}{\partial t}$ (ft/day)
0	1000	1.0000	0.7306	1.0000	0.1534	0.00001227	1.06
1000	2000	0.7306	0.5338	0.1534	0.0235	0.00000809	0.70
2000	3000	0.5338	0.3900	0.0235	0.0036	0.00000577	0.50
3000	4000	0.3900	0.2850	0.0036	0.0006	0.00000420	0.36
4000	5000	0.2850	0.2082	0.0006	0.0001	0.00000306	0.26
5000	6000	0.2082	0.1521	0.0001	0.0000	0.00000224	0.19

Long-Term Morphologic Response to the Presence of a Sediment Diversion. To investigate the long term effects of river diversions (i.e., how changes in riverine sediment load can affect river morphology), it is useful to revisit the methods used in the upstream drawdown analysis. For this portion of the analysis, however, the assumption of constant channel width is abandoned: i.e., the channel width downstream of the diversion is included as a variable.

Two equations can be written to compute the increase in stream power required to reestablish equilibrium downstream. They are derived by substituting Equation (1) into Equations (2) and (3), and equating the saturated condition at cross-section 3 with a new equilibrium condition. Since the downstream conditions are to be final conditions (a new equilibrium) it is required that uniform flow conditions exist (i.e., the hydraulic slope is equal to the bed slope). For convenience, the equations have common terms canceled out:

$$\phi_3 \beta_{S.3} h_3^{\frac{5n_S}{3}} S_b^{\frac{3n_S}{2}} b_3 = \beta_{S.3F} h_{3F}^{\frac{5n_S}{3}} S_{b.3F}^{\frac{3n_S}{2}} b_{3F} \quad (36)$$

$$\phi_3 (1 - \beta_{S.3}) h_3^{\frac{5n_B}{3}} S_b^{\frac{3n_B}{2}} b_3 = (1 - \beta_{S.3F}) h_{3F}^{\frac{5n_B}{3}} S_{b.3F}^{\frac{3n_B}{2}} b_{3F} \quad (37)$$

Equations (36) and (37) contain four unknowns: $S_{B.3F}$, h_{3F} , b_{3F} , and $\beta_{S.3F}$. Therefore, two additional equations are required. One of these is obtained by invoking Manning's equation and enforcing the conservation of water mass.

$$h_3^{5/3} S_b^{1/2} b_3 = h_{3F}^{5/3} S_{b.3F}^{1/2} b_{3F} \quad (38)$$

The remaining equation results from specifying a value for one of the unknowns.

If the downstream width is specified, Equations (36)-(38) can then be solved for $\beta_{S.3F}$, h_{3F} , and $S_{b.3F}$:

$$\beta_{S.3F} = 1 - \phi_3 (1 - \beta_{S.3}) \left(\frac{\phi_3 \beta_{S.3}}{\beta_{S.3F}} \right)^{\frac{-n_B}{n_S}} \left(\frac{b_3}{b_{3F}} \right)^{\frac{2n_S + 1 - 3n_S n_B}{2n_S}} \quad (39)$$

$$h_{3F} = h_3 \left(\frac{\phi_3 \beta_{S,3}}{\beta_{S,3F}} \right)^{\frac{-3}{10n_s}} \left(\frac{b_3}{b_{3F}} \right)^{\frac{9n_s-3}{10n_s}} \quad (40)$$

$$S_{b,3F} = S_b \left(\frac{\phi_3 \beta_{S,3}}{\beta_{S,3F}} \right)^{\frac{1}{n_s}} \left(\frac{b_3}{b_{3F}} \right)^{\frac{1-n_s}{n_s}} \quad (41)$$

Note that Equation (39) can be solved by iteration.

Figure 5 depicts the results of the solutions for Equations (39)-(41), assuming a constant width condition ($b_{3F} = b_3$). The solution employs the input parameters assumed in the Approximate Values for Input Parameters section of this report (including $\varepsilon_D = 1$). Figure 5 shows that, for these input conditions, the downstream slope is always steeper than the upstream slope. This is because the specified sediment diversion efficiency is less than the equilibrium value. Since the solution requires downstream equilibrium, this must result in downstream deposition to establish the new slope. If the specified diversion ratio were greater than the equilibrium value, the downstream slope would be milder than the upstream slope, and downstream erosion would result.

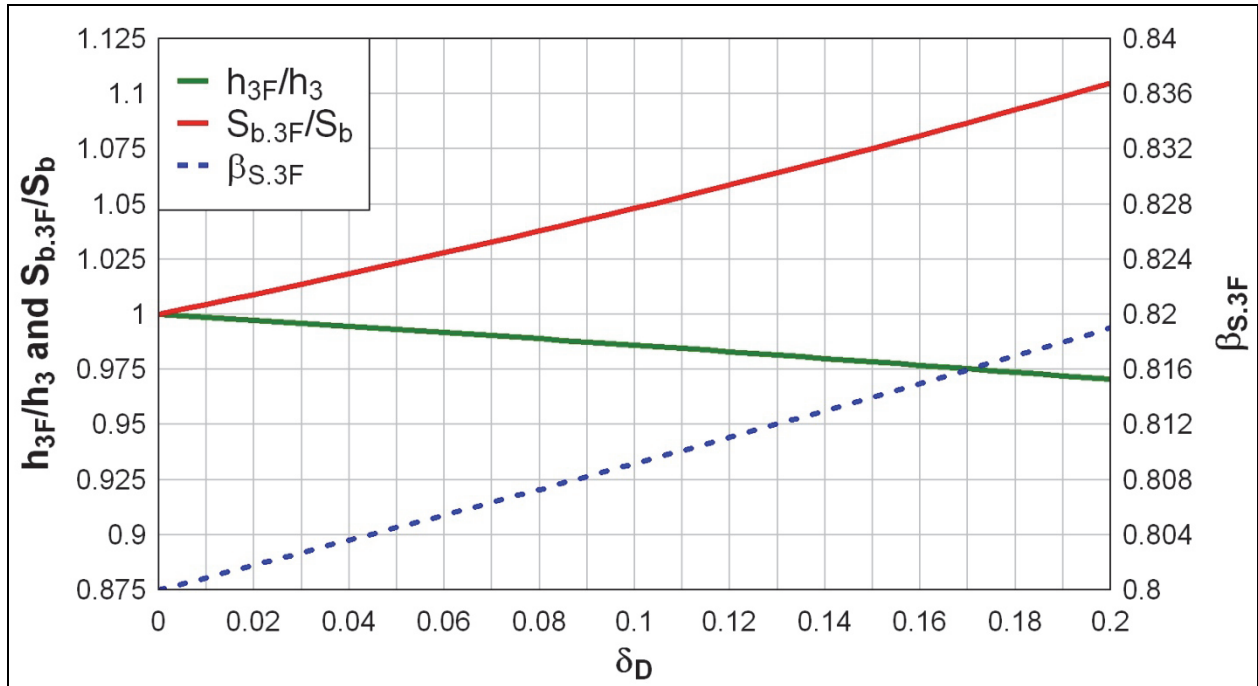


Figure 5. Final downstream equilibrium conditions for a sediment diversion efficiency of 1.

Figure 6 is a simplified, schematic depiction of various ways in which different sediment diversion efficiencies will impact the river morphology upstream and downstream of the diversion site, for a constant river width condition. These diagrams are similar to one given by Raudkivi (1993).

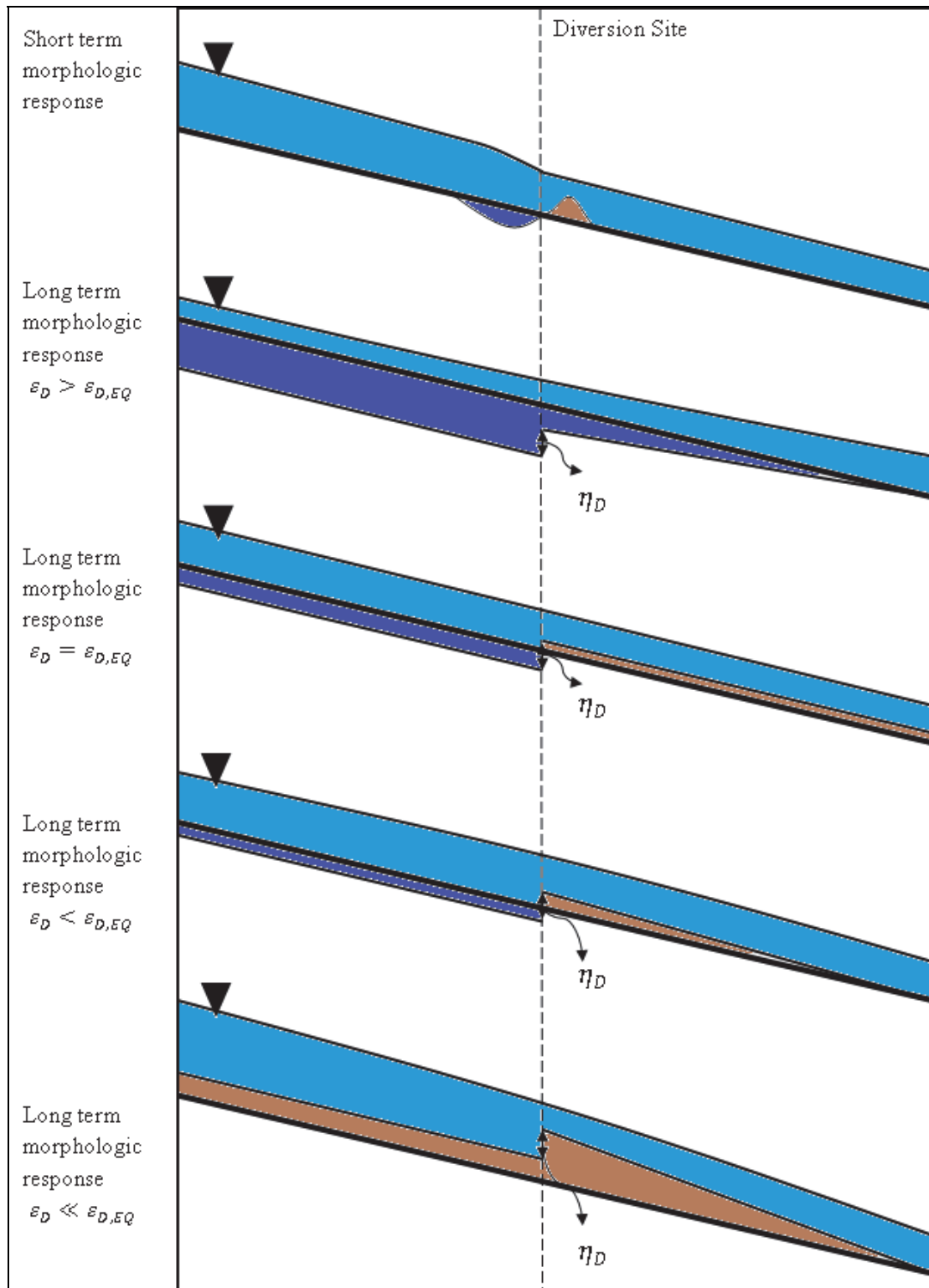


Figure 6. Short term and long term effects on river morphology due to the presence of a sediment diversion with various sediment diversion efficiencies, for a constant width condition.

At the onset of diversion operations, the river begins to scour upstream of the diversion, and to deposit downstream of the site. The results of the equilibrium diversion analysis depicted in Figure 3 show clearly that this initial response will occur regardless of the sediment diversion efficiency.

In contrast to this, the way in which this initial perturbation of the river morphology progresses to a final long term adjustment is entirely dependent on the sediment diversion efficiency. Figure 6 depicts four general results that correspond to four different relative values of the sediment diversion efficiency:

- $\varepsilon_D > \varepsilon_{D.EQ}$ (downstream erosion and significant upstream channel degradation)
- $\varepsilon_D = \varepsilon_{D.EQ}$ (mild downstream deposition and moderate upstream channel degradation)
- $\varepsilon_D < \varepsilon_{D.EQ}$ (moderate downstream deposition and mild upstream channel degradation)
- $\varepsilon_D \ll \varepsilon_{D.EQ}$ (significant downstream deposition and upstream deposition)

In all cases, there is some adjustment of the river morphology upstream and downstream of the diversion site. This is even true for the equilibrium case. To understand why, it is instructive to consider the basic constraints that influence these morphologic trends. (Note that these constraints are partly due to the simplifying assumptions associated with this analysis; a real river is much more dynamic and heterogeneous than this idealized case):

- The river will adjust to a uniform flow conditions both upstream and downstream of the diversion.
- This means that the water surface slope upstream and downstream of the diversion must be parallel to the bed and the depth upstream and downstream of the diversion must be uniform flow depth, as given by Manning's equation.
- Since the river width is constant, the depth ratio between the upstream and downstream sections must be given by Equation (5).
- Since the water surface elevation must be the same at the diversion site, the relative displacement of the bed (between downstream and upstream) must be given by the following equation (derived from Equation (5)):

$$\frac{\eta_D}{h_1} = 1 - (1 - \delta_D)^{3/5} \quad (42)$$

- The downstream slope adjustment is given by Equation (41). This adjustment is accomplished by erosion of or deposition to the bed until a new slope is established.
- For depositional conditions, the final degree of deposition is dependent on the distance downstream to the next break in the hydraulic grade line (e.g., backwater conditions, a change in channel cross-sectional area, etc.). This *reach length* (L_R) is dependent on site specific conditions, but it can be many miles for a large river.

- If the reach length is greater than a critical reach length ($L_{R,CR}$) the river will deposit sufficient sediment to create a backwater effect at the diversion site, and deposition will progress upstream of the diversion. This critical reach length is given as follows:

$$L_{R,CR} = \frac{\eta_D}{S_{b,3F} - S_b} \quad (43)$$

As an example, consider a 20 percent flow diversion from a river with conditions approximating those in the Lower Mississippi River: i.e., $h_I = 40$ feet, and $S_b = 0.00005$. From Figure 5, $S_{b,3F} = 0.0000555$. For these conditions, Equation (42) gives a value of $\eta_D = 5.0$ feet, and Equation (43) gives a value of $L_{R,CR} = 173$ miles. As long as the reach length L_R is less than this critical value, deposition should not progress upstream of the diversion site.

Real changes in river morphology are much more complex than this simple analysis. In addition to complexities in river geometry and hydrograph characteristics, this analysis has not considered changes in sediment supply, sediment types, grain sorting, armoring, and many other basic river processes. However, in spite of these simplifications, the general trends associated with this simple analysis can serve to provide a basic understanding of the types of riverine morphologic responses to be expected from the introduction of a diversion.

Mitigation of Riverine Morphologic Response to a Sediment Diversion by Artificial Constriction of the Downstream Cross-section (e.g., Training Dikes). The morphologic trends depicted in Figure 6 consider the basic morphologic response of the river assuming a constant width condition. However, river width is not generally a constant. River width can vary naturally, or the width can be modified artificially through the use of structures such as training dikes.

It is useful, therefore, to determine what downstream width conditions are required to maintain the same downstream slope as the upstream slope. This condition is effectively a minimization of the riverine morphologic impacts, since no downstream slope adjustment is required. These conditions can be found by specifying equal slopes ($S_{B,3F} = S_{B,3}$), and solving Equations (36)-(38) for $\beta_{S,3F}$, h_{3F} , and b_{3F} :

$$\beta_{S,3F} = 1 - \phi_3 (1 - \beta_{S,3}) \left(\frac{\phi_3 \beta_{S,3}}{\beta_{S,3F}} \right)^{\left(\frac{1}{n_S - 1} \left(\frac{2n_S + 1 - 3n_S n_B}{2n_S} \right) - \frac{n_B}{n_S} \right)} \quad (44)$$

$$h_{3F} = h_3 \left(\frac{\phi_3 \beta_{S,3}}{\beta_{S,3F}} \right)^{\frac{3}{10n_S} \left(\frac{1 - 3n_S}{1 - n_S} - 1 \right)} \quad (45)$$

$$b_{3F} = b_3 \left(\frac{\phi_3 \beta_{S,3}}{\beta_{S,3F}} \right)^{\frac{1}{1 - n_S}} \quad (46)$$

Equation (44) can be solved by iteration.

Figure 7 depicts the results of the solutions for Equations (44)-(46). The solution employs the input parameters assumed in the Approximate Values for Input Parameters section of this report (including $\varepsilon_D = 1$). Similar results for a constricted downstream section are given by Raudkivi (1993).

OTHER IMPORTANT CONSIDERATIONS: The analysis given here is strictly applicable only for the conditions given in the Simplification and Initial Conditions section of this report. However, real rivers are subject to many important processes and complicating factors that do not satisfy these conditions. This section addresses several of these factors, and discusses how they will tend to influence the interpretation of the analysis.

Erosion Resistant Substrate and Armored Bed Gradation Effects. In the Lower Mississippi River, observations have demonstrated that the river bed consists of a sand layer of variable thickness, underlain by erosion resistant strata (either relict glacial deposits or sand deposits cemented by clays). The sand layer thickness varies from several meters thick in lateral bars, to near zero thickness in the deep thalweg of the river (Allison and Nittrouer 2004).

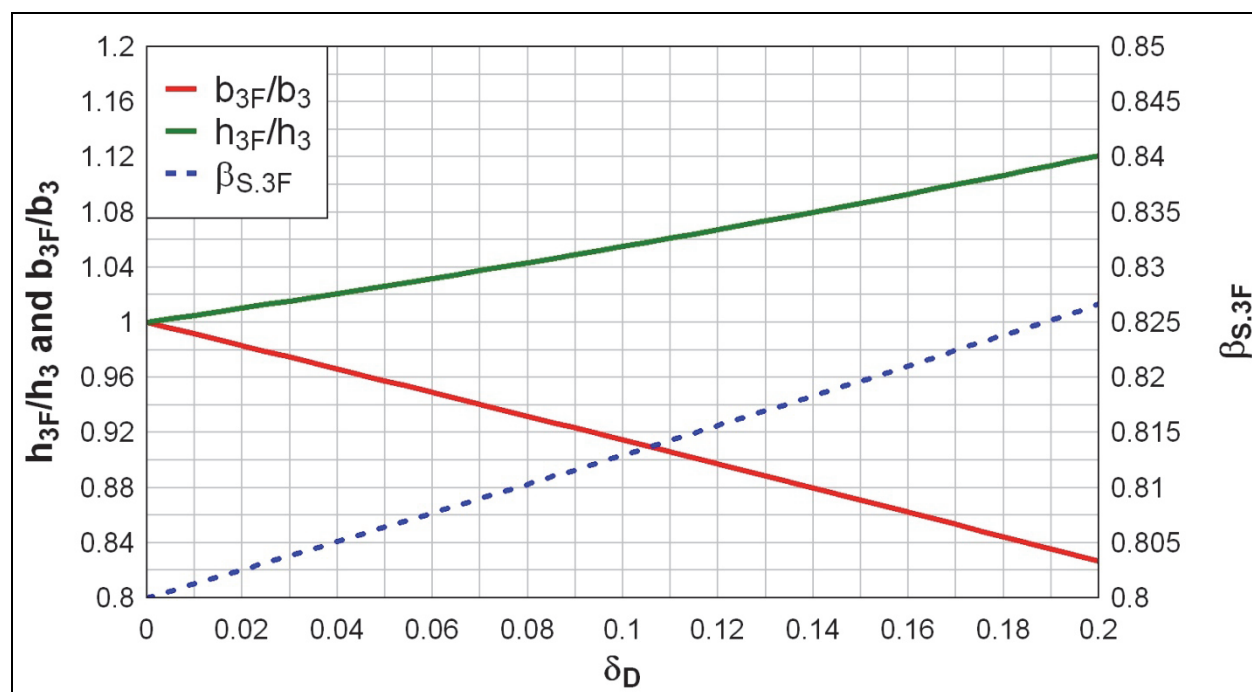


Figure 7. The downstream river width adjustment required to maintain a constant slope in the river (Minimum Morphologic Impact Condition)

Further upstream in the river, gravel sized sediment can be found in bed samples collected in the river thalweg (Little et al. 2012). These sediment classes are generally immobile, except at very high flows.

Both of these conditions can be more generally categorized as supply limited conditions. That is, the available stream power has the potential to transport more sediment than is available in the bed, due either to exposed non-erodable bed (erosion resistant substrate) or to exposed non-erodable grains (armored bed gradation).

Supply limited conditions can be incorporated into the analytic framework given in this report, in a qualitative sense. This is done by recognizing that supply limited conditions imply a baseline value of the saturation ratio that is less than 1.

Let ϕ_{SL} be defined as the saturation ratio due to supply limited conditions. For an erosion resistant substrate, ϕ_{SL} is defined as follows:

$$\phi_{SL} = 1 - \frac{A_{B,ERS}}{A_B} \quad (47)$$

Where $A_{B,ERS}$ is the surface area of the bed where there is exposed erosion resistant substrate, and A_B is the total surface area of the bed.

For an armored bed gradation, ϕ_{SL} is defined as follows:

$$\phi_{SL} = 1 - \beta_{NE} \quad (48)$$

Where β_{NE} is the fraction of the total sediment gradation that consists of non-erodable grains.

The existence of supply limited conditions in a river means that the river has the capacity to carry more of the sediment classes that are in active transport (i.e., the erodible classes) than it currently carries. This means that a diversion that would tend to induce downstream deposition for a river that is not supply limited may, under supply limited conditions, have a more complex response that does not result in net deposition. This downstream response might include, for example, the adjustment of channel morphology, such as point bars and/or lateral bars, or an increase in the fraction of bed material that consists of erodible grains (bed material fining).

For this analysis, a threshold condition can be defined that determines whether or not the downstream response of a river in supply limited conditions is likely to result in net deposition:

- If $\phi_3 \phi_{SL} > 1$, expect net deposition downstream of the diversion.
- If $\phi_3 \phi_{SL} < 1$, expect supply limited response downstream of the diversion (e.g., adjustment of channel morphology and/or downstream bed material fining).

For example, Allison and Nittrouer (2004) established that about 1/3 of the Mississippi riverbed below New Orleans is exposed relict strata. From Equation (47), this represents a value of $\phi_{SL} = 1 - 1/3 = 0.667$. Assuming the same general input parameters given in the Approximate Values for Input Parameters section of this report and a value of the diversion fraction $\delta_D = 0.2$, the short term value of $\phi_3 = 2.75$ and the long term value of $\phi_3 = 1.2$ obtain (these values of ϕ_3 are taken from Figure 4). Hence, the short-term product $\phi_3 \phi_{SL} = 2.75 \times 0.667 = 1.83 > 1$, and the long-term product $\phi_3 \phi_{SL} = 1.2 \times 0.667 = 0.8 < 1$. This means that the short-term downstream response can be expected to be net deposition, whereas the long-term downstream response can be expected to be a supply limited response (adjustment without net deposition)

Nonuniform Flow Effects. As a river approaches a downstream control, the river transitions from uniform flow conditions to nonuniform flow conditions. If the downstream control accelerates the flow, such as at a cross-section contraction or at a water diversion, the nonuniform flow condition is

a drawdown condition, where the hydraulic slope grows steeper as one proceeds downstream to the control point. If the downstream control decelerates the flow, such as at a cross-section expansion or at an open water boundary, the nonuniform flow condition is a backwater condition, where the hydraulic slope grows milder as one proceeds downstream to the control point.

If a diversion is located upstream of a drawdown control, the stream power of the river increases in the downstream direction. Therefore, the river has more capacity to transport sediment, so any potential downstream deposition from the introduction of the diversion will be mitigated to some degree (relative to uniform flow conditions) by the drawdown of the river. The sediment will tend to be moved downstream past the drawdown control, where it may deposit (depending on conditions in the river downstream of the control).

If a diversion is located upstream of a backwater control, the stream power of the river decreases in the downstream direction. Therefore, the river has less capacity to transport sediment, so any potential downstream deposition from the introduction of a diversion will be augmented to some degree (relative to uniform flow conditions) by the backwater effect.

An important exception to this principle occurs as the stream power in the river successively drops below the transport threshold of each non-cohesive grain class. For this condition, most of the assumptions employed in the analysis given in this report are not valid, and other considerations govern the response of the river to the presence of a sediment diversion.

As the backwater curve approaches zero slope at the downstream end, the bed shear stress in the river decreases until it falls below the critical shear stress of each of the non-cohesive grains, progressing from coarser to finer grains as one travels downstream. As the critical shear stress threshold of each grain is crossed, the river loses the ability to transport that grain class, and all of the remaining sediment of that class deposits in the riverbed, or in the river delta. This condition is observed at the Mississippi River, just south of Venice, La. The presence of several diversions and passes at this location cause a rapid reduction in the transport potential of the river, and most of the remaining sand in the river falls out into the riverbed (Sharp et al. 2013).

The location of each of these transport thresholds is a function of the shape of the backwater curve, which in turn is a function of the river discharge. Any reduction in river discharge will cause the backwater curve to migrate upstream; hence, each of the transport thresholds will migrate upstream. This means that a sediment diversion located upstream in the river will, in the long term, tend to cause the location of the deposition associated with each of the downstream transport thresholds to migrate upstream.

In addition, since the deposition associated with each transport threshold includes all of the sediment that remains in the river of the grain class associated with that threshold, an upstream sediment diversion that removes any sediment of that class will, in the long term, *decrease* the deposition associated with the downstream sediment threshold (although a short term increase in deposition might result from the short term increase in sediment supply due to the drawdown induced erosion upstream of the diversion). This long term reduction in deposition will occur irrespective of the sediment diversion efficiency associated with the diversion: the reduction in deposition is *greater* for larger values of the sediment diversion efficiency, but any sediment

diversion efficiency greater than zero will result in some reduction of deposition at the transport threshold.

Thus, in the long term, a sediment diversion located in a river upstream of the transport threshold of a given non-cohesive grain class will result in both the upstream migration and the net reduction of the deposition associated with the transport threshold of that grain class.

Unsteady Flow Effects. The preceding analysis addressed only steady or quasi-steady flow conditions; however, all real flows are unsteady flows, and these unsteady effects must be considered when designing diversions. Typically, there is an observed hysteresis in sediment transport associated with a river hydrograph: sediment concentration tends to be much higher on the rising limb of the hydrograph than on the falling limb. Although this phenomenon is evident for both cohesive and non-cohesive sediment classes, the cause is different in each case. The hysteresis in cohesive sediment concentration is due primarily to the mobilization of sediments from the contributing watersheds by soil erosion, stream bank erosion, and the remobilization of sediments stored in slack water deposits on the rising limb. The hysteresis in non-cohesive sediment concentration is due primarily to the increased hydraulic slope of the river and armoring of the sediment bed on the rising limb. For a given discharge, the same river will have a steeper slope on the rising limb than on the falling limb, due to the progression of the flood wave. Using the same stream power arguments used in the preceding sections, this means that the river has a greater sediment transport potential on the rising limb than on the falling limb. Also, the increased erosion on the rising limb preferentially extracts finer grain classes from the bed, resulting in an armored bed condition on the falling limb. This armored condition limits the sediment supply, further reducing the sediment transport rate on the falling limb.

If a given sediment diversion is designed with a control structure, it can be operated to take advantage of this hysteresis. For example, it can be opened during the rising limb of flood hydrographs to maximize sediment capture. However, the intermittent operation of a control structure can have effects on the shape of the flood hydrograph, and hence can affect the hydrology of the river and floodplain in a manner analogous to the operation of a reservoir (Lindner 1953). Therefore, if intermittent diversion operations are proposed, a thorough and dynamic analysis of the flood characteristics of the river with and without diversion operations should be undertaken to investigate these effects.

Multiple Diversion Effects. If there are multiple sediment diversions present in a river, the diversions will tend to interact in a nonlinear and complex fashion. For example, the drawdown induced by a given diversion will influence the water level and sediment load associated with an upstream diversion (provided that the distance to this upstream diversion is within the influence length of the drawdown curve associated with the downstream diversion). In turn, the upstream diversion will influence the water discharge and sediment load that reaches the downstream diversion. The complexities inherent in these interactions dictate the need for sophisticated basin-scale numerical or physical model analyses to fully quantify the impacts of multiple sediment diversions.

SUMMARY OF THE ANALYSIS: This document consists of a simplified analytic description of the effects of a sediment diversion on the sediment transport processes and morphologic response of a river. The analysis is based on the assumption of a wide rectangular river, at steady

(or quasi-steady), uniform flow throughout its length (before the introduction of the diversion). It is also assumed that the diversion is a relatively small fraction of the total river discharge (e.g., less than 25 percent). Hence, because of these simplifications, the results of this analysis are intended to illustrate trends and tendencies only. The following is a list of the primary general conclusions that can be drawn from the analysis:

- The sediment transport and morphologic effects of the introduction of a sediment diversion into a river can be generally categorized as *short term* effects and *long term* effects.
- Short term changes are changes associated with the initial response of the river to the introduction of a diversion. For large rivers, these changes begin at the initiation of diversion operations and last from several years to a decade. Long term changes are changes that are associated with the long term adjustment of the river to the presence of the diversion. For a large river, the duration of these changes is typically on the scale of decades.
- When the diversion is initially opened, it induces a drawdown in the river upstream of the diversion. This accelerates the flow just upstream of the diversion, eroding the bed and supersaturating the river with sediment. The extent of bed erosion may be limited by the thickness of upstream bed sediment layers and armoring of the bed surface by the coarser fraction of the bed material.
- The reduction in river flow downstream of the diversion causes a corresponding reduction in sediment transport potential. Unless the supply of sediment from upstream is less than the reduced transport potential, deposition will occur downstream of the diversion.
- Because of the initial increase in the sediment load from the upstream reach, for all practical purposes, it is not feasible to design a diversion that will be in downstream equilibrium in the short term, due to the drawdown induced increase in sediment load.
- As time progresses, the river upstream of the diversion site adjusts to the drawdown induced by the diversion, and the sediment load in the river reduces to the equilibrium value.
- For this long term condition, the sediment diversion efficiency required to maintain downstream equilibrium is generally greater than 1. For the specific input parameters given in this analysis, the sediment diversion efficiency falls between a value of 1.7 and 1.8 for all of the diversion discharge fractions investigated (0 to 0.2). But it is important to note that other input parameters will yield different results. The equilibrium diversion efficiency is inversely proportional to the fraction of water diverted.
- A relatively high sediment diversion efficiency can potentially be achieved with a diversion designed to access sediment-rich environments in the river (e.g., at the inside of a river bend or atop a lateral bar). However, the ability to transport this sediment-rich water through the diversion site and out of the receiving area is constrained by the available potential energy (head difference) at the diversion site. Also, the long-term sediment diversion efficiency may change in response to local morphological changes.

- Since it is often not feasible to design a diversion with a large enough sediment diversion efficiency to achieve equilibrium, it is useful to investigate the effects of a diversion with an efficiency less than this value. For this analysis, a sediment diversion efficiency of 1 was selected.
- For a sediment diversion efficiency less than the equilibrium value, the short term increase of the riverine sediment load (downstream of the diversion) is significantly larger than the long term increase. In the long term, the effects can still be of enough significance to influence river morphology. For example, with a 10 percent flow diversion, the effect is roughly a 10 percent increase in sediment load.
- In general, a sediment diversion will tend to induce downstream conditions for which a greater fraction of grains move as suspended load (a finer sediment bed). This downstream fining effect is more pronounced for sediment rich diversions than for sediment poor diversions since, sediment rich diversions tend to divert a higher proportion of bed load than do sediment poor diversions.
- The effect of the sediment diversion on river morphology can also be considered in terms of short term and long term effects.
- At the onset of diversion operations, the river begins to scour upstream of the diversion, and to deposit downstream of the site. A simplified methodology that can be used to provide an estimate of the rate of deposition downstream of a diversion upon initiation of diversion operations is given in Equations (26)-(35).
- In the long term, a new equilibrium is reestablished upstream and downstream of the diversion. The morphologic changes required to establish this equilibrium are dependent on the sediment diversion efficiency:
 - $\varepsilon_D > \varepsilon_{D.EQ}$ (downstream erosion and significant upstream channel degradation)
 - $\varepsilon_D = \varepsilon_{D.EQ}$ (mild downstream deposition and moderate upstream channel degradation)
 - $\varepsilon_D < \varepsilon_{D.EQ}$ (moderate downstream deposition and mild upstream channel degradation)
 - $\varepsilon_D \ll \varepsilon_{D.EQ}$ (significant downstream deposition and upstream deposition)
- In all cases, there is some adjustment of the river morphology upstream and downstream of the diversion site. This is even true for the equilibrium case.
- It is possible to alter the morphologic response of the river by artificially constricting the channel downstream of the diversion (e.g., with training dikes). Therefore, it is useful to determine what downstream width conditions are required to maintain the same downstream slope as the upstream slope. This condition is effectively a minimization of the riverine morphologic impacts, since no downstream slope adjustment is required. Equations (44)-(46) give the necessary river width adjustment and consequent river depth and suspended load fraction adjustments.
- Real changes in river morphology are much more complex than this simple analysis. On a regional scale, the river slope usually decreases in the downstream direction and local variations in slope may result from channel constrictions, geological controls, and other

changes in channel geometry. In addition to complexities in river geometry and hydrograph characteristics, this analysis has not considered changes in sediment supply, sediment types, grain sorting, armoring, and many other basic river processes.

- Although physical and/or numerical models are required to provide robust analyses of the impacts of these complexities, some qualitative trends can be investigated in the context of this simple analysis.
- Supply limited conditions exist in the river when the available stream power has the potential to transport more sediment than is available in the bed, due either to exposed non-erodible bed (erosion resistant substrate) or exposed non-erodible grains (armored bed gradation).
- The existence of supply limited conditions in a river means that the river has the capacity to carry more of the sediment classes that are in active transport (i.e., the erodible classes) than it currently carries. This means that a diversion that would tend to induce downstream deposition for a river that is not supply limited may, under supply limited conditions, have a more complex response that does not result in net deposition.
- This downstream response might include, for example, the adjustment of channel morphology, such as point bars and/or lateral bars, or an increase in the fraction of bed material that consists of erodible grains (bed material fining).
- If a diversion is located upstream of a drawdown control, the stream power of the river increases in the downstream direction. Therefore, the river has more capacity to transport sediment, so any potential downstream deposition from the introduction of the diversion will be mitigated to some degree (relative to uniform flow conditions) by the drawdown of the river.
- If a diversion is located upstream of a backwater control, the stream power of the river decreases in the downstream direction. Therefore, the river has less capacity to transport sediment, so any potential downstream deposition from the introduction of a diversion will be augmented to some degree (relative to uniform flow conditions) by the backwater effect.
- An important exception to this principle occurs as the stream power in the river successively drops below the transport threshold of each non-cohesive grain class.
- For this condition, in the long term, a sediment diversion located in a river upstream of the transport threshold of a given non-cohesive grain class will result in both the upstream migration and the net reduction of the deposition associated with the transport threshold of that grain class.
- Although this analysis is for steady or quasi-steady flows, all real flows are unsteady flows, and these unsteady effects must be considered when designing diversions.
- Typically, there is an observed hysteresis in sediment transport associated with a river hydrograph. Sediment concentration tends to be much higher on the rising limb of the hydrograph than on the falling limb.

- If a given sediment diversion is designed with a control structure, it can be operated to take advantage of this hysteresis. For example, it can be opened during the rising limb of flood hydrographs to maximize sediment capture.
- However, the intermittent operation of a control structure can have effects on the shape of the flood hydrograph, and hence can affect the hydrology of the river and floodplain in a manner analogous to the operation of a reservoir. Therefore, if intermittent diversion operations are proposed, a thorough and dynamic analysis of the flood characteristics of the river with and without diversion operations should be undertaken to investigate these effects.
- If there are multiple sediment diversions present in a river, the diversions will tend to interact in a nonlinear and complex fashion. The complexities inherent in these interactions dictate the need for sophisticated basin-scale numerical or physical model analyses to fully quantify the impacts of multiple sediment diversions.

CONCLUSIONS: This technical note details the results of an analytic treatment of an idealized sediment diversion. These results can be used to provide a preliminary assessment of the riverside effects of a sediment diversion. The primary conclusions of the analysis are as follows:

- When a diversion is initially opened, it induces a drawdown in the river upstream of the diversion. This accelerates the flow just upstream of the diversion, eroding the bed and supersaturating the river with sediment.
- Because of this initial increase in the sediment load from the upstream reach, for all practical purposes it is not feasible to design a diversion that will inhibit the initial deposition downstream of the diversion. There will always be some transfer of bed material from upstream to downstream of the diversion. This process will persist until the river morphology has adjusted to the presence of the diversion.
- As time progresses, the river upstream of the diversion site adjusts to the drawdown induced by the diversion, and the inflowing sediment load reduces to the equilibrium value.
- The sediment diversion efficiency required to maintain downstream sediment equilibrium can be estimated using techniques given in this technical note.
- In the long term, a new sediment equilibrium is established in the river upstream and downstream of the diversion. The morphologic changes required to establish this equilibrium are dependent on the sediment diversion efficiency. The qualitative trends are given as follows (as depicted in Figure 6):
 - If $\varepsilon_D > \varepsilon_{D,EQ}$, there is likely to be downstream erosion and significant upstream channel degradation.
 - If $\varepsilon_D = \varepsilon_{D,EQ}$, there is likely to be mild downstream deposition and moderate upstream channel degradation.
 - If $\varepsilon_D < \varepsilon_{D,EQ}$, there is likely to be moderate downstream deposition and mild upstream channel degradation.

- If $\varepsilon_D < \varepsilon_{D,EQ}$, there is likely to be significant downstream deposition and upstream deposition.
- The quantitative trends are dependent on specific diversion characteristics. Some techniques for estimating these quantities are given in this technical note.
- It is possible to alter the morphologic response of the river to a diversion by artificially constricting the channel downstream of the diversion (e.g., with training dikes). Therefore, it is useful to determine what downstream width conditions are required to maintain the same downstream slope as the upstream slope. This condition is effectively a minimization of the riverine morphologic impacts. A simple technique to estimate these downstream width conditions is given in this technical note.
- Although this analysis is for steady or quasi-steady flows, all real rivers are nonuniform, unsteady phenomena, with active bed sorting and armoring processes. These effects must be considered when designing diversions. Some techniques for investigating the basic trends associated with these complexities are given in this technical note.

Real changes in river sediment transport and morphology are much more complex than this simple analysis. In addition to complexities in river geometry and hydrograph characteristics, this analysis cannot be used to quantify the effects of changes in sediment supply, sediment types, grain sorting, armoring, and many other basic river processes. Hence, in order to fully evaluate any proposed sediment diversion, it is necessary to develop robust numerical and/or physical models, informed by quality field observations and morphologic analyses.

DEFINITIONS OF SYMBOLS

A_B	=	The surface area of the sediment bed
$A_{B,ERS}$	=	The surface area of the sediment bed that consists of an erosion resistant substrate
b	=	The river width
b_F	=	The final river width (after long term readjustment)
$C_{P,S}$	=	The suspended sediment concentration potential
$C_{B,S}$	=	The bed load concentration potential
C_S	=	The suspended sediment concentration
$C_{S,EQ}$	=	The suspended sediment equilibrium concentration
f_B	=	The bed load concentration excess fraction
f_S	=	The suspended concentration excess fraction
h	=	The river depth
h_F	=	The final river depth (after long term readjustment)
K_n	=	The Manning's units constant
$L_{D11\%}$	=	The drawdown influence length to 1% of maximum drawdown
$L_{D150\%}$	=	The drawdown influence length to 50% of maximum drawdown
L_R	=	The length of the river reach
$L_{R,CR}$	=	The critical length of the river reach, for determining backwater conditions at the diversion site
n	=	The Manning's n
n_B	=	The power law exponent for bed load transport in terms of stream power
n_S	=	The power law exponent for suspended load transport in terms of stream power

Q	=	The water discharge in the river
$Q_{B.POT}$	=	The bed load sediment transport potential
Q_D	=	The water discharge in the diversion
Q_S	=	The total sediment discharge in the river
$Q_{S.POT}$	=	The suspended load sediment transport potential
Q_{SD}	=	The total sediment discharge in the diversion
$Q_{S.B}$	=	The bed load sediment discharge in the river
$Q_{S.S}$	=	The suspended load sediment discharge in the river
$Q_{SD.B}$	=	The bed load sediment discharge in the diversion
$Q_{SD.S}$	=	The suspended load sediment discharge in the diversion
r	=	The Rouse sediment profile coefficient
S	=	The slope of the hydraulic grade line (i.e., the friction slope)
S_b	=	The slope of the river bed
$S_{b.F}$	=	The final slope of the river bed (after long term readjustment)
u	=	The cross-sectionally averaged velocity
u_f	=	The friction velocity
w_S	=	The settling velocity of the median bed grain diameter (d_{50})
α_B	=	The power law coefficient for bed load transport in terms of stream power
α_S	=	The power law coefficient for suspended load transport in terms of stream power
β_{NE}	=	The fraction of bed sediment that is non-erodable
β_S	=	The fraction of bed sediment moving as suspended load
$\beta_{S.EQ}$	=	The fraction of bed sediment moving as suspended load for equilibrium conditions
$\beta_{S.F}$	=	The final fraction of bed sediment moving as suspended load (after long term readjustment)
δ_D	=	The fraction of river discharge diverted into the sediment diversion
ε_D	=	The sediment diversion efficiency
$\varepsilon_{D.EQ}$	=	The sediment diversion efficiency for equilibrium conditions
η	=	The bed displacement
η_D	=	The maximum change in bed displacement associated with the diversion
ρ	=	The water density
ϕ	=	The sediment load saturation ratio
ϕ_{SL}	=	The sediment load saturation ratio due to supply limited conditions
ζ_S	=	The suspended sediment turbulence correction factor

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